Using the Multirhodotron as an Advanced Rhodotron

Abstract

This article assesses the use of the new type of electron accelerator - Multirhodotron to energize FEL at the megawatt level of power in the continuous wave (CW) mode and for "electron cooling" in proton accelerators and colliders.

More than 30 years ago, Pottier and Nguyen suggested a new idea regarding the acceleration of an electron beam in the radial electrical field of the coaxial resonant cavity energized by the TEM_1 mode [1]. Accelerators of this type were trademarked as Rhodotrons. For 30 years, the Belgian company IBA manufactured the entire line of these accelerators (TT 50-TT 1000) with power from 50 to 1000 kW for electron energy at an output of up to 10 MeV [2]. These 100-200 MHz accelerators have excessively large cavity dimensions. Their radiuses and weights are up to 1-1.3 meters and 8-10 tons, respectively. Such accelerators allow only 7-10 passes of an electron beam through the cavity because all of the trajectories of an electron beam lay in the single middle plane of the cavity. The large electrical gap where all of the electrons of the beam obtain the first acceleration after injection from a non-relativistic injector (80-100 kV) provides good capture of the electrons into the acceleration region. Simulations of electron dynamics in this gap have shown that all of the electrons that are in an interval with a length of π/2 are grouping in the interval which will be in four times smaller, with a length of approximately ~π/8, providing a 25% capture rate. This is shown in FIG. 1.

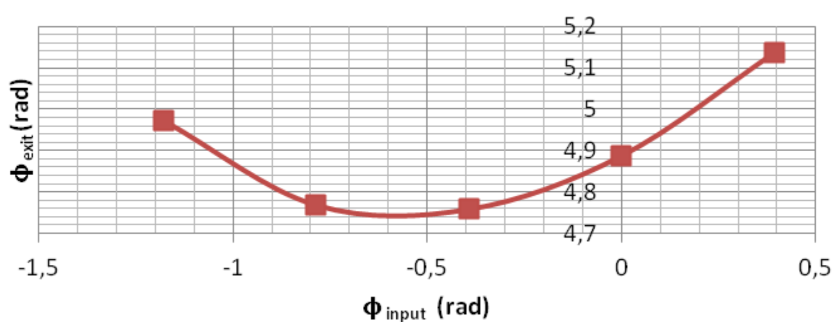


FIG. 1

Since each passage through the cavity provides approximately 1 MeV of energy after the first passage, all electrons captured in the region of acceleration will be relativistic and with velocities near the speed of light. This assumption allows the integration of the radial equation of the electrons' motion in the cavity for the next passages in the finite view.

$$P_{(n+1)} = P_{(n)} + \Delta P_0 \cos (R\omega/c + \varphi) \qquad (1),$$

where $P_{(n+1)}$ and $P_{(n)}$ are respectively the impulses of motion after (n+1) and (n) passages through the cavity, ΔP_0 is the maximum of the change of the impulse of the motion of the electrons in the cavity for one passage, R is the external radius of the Rhodotron's coaxial cavity, c is the speed of light, $\omega = 2\pi f$, and φ is the phase of the input of each electron into the cavity.
After (n) passes, the total impulse of the motion of the accelerating electrons in the beam is

$$P_{(n)} = P_{(0)}+n\, \Delta P_0 \cos (R\omega/c+\varphi_0+\Delta\varphi) \approx P_{(0)}+n\, \Delta P_0(1- 0.5\, \Delta\varphi^{**}2) = P_{(0)} + n\, \Delta P_0(1-0.076) \qquad (2)$$

where: $R\omega/c +\varphi_0 = 0$ is the phase of the acceleration's maximum and $\Delta\varphi = \pi/8$ is the boundary of the capture in acceleration.

The simulation of the initial stage of acceleration for four passages through the cavity is illustrated in FIG. 2. The trajectories of the electrons with $\varphi = -1.5708$ (Series 6) and $\varphi = 0.7854$ (Series 7) are also shown. These trajectories (Series 6, 7) further exit the acceleration region.

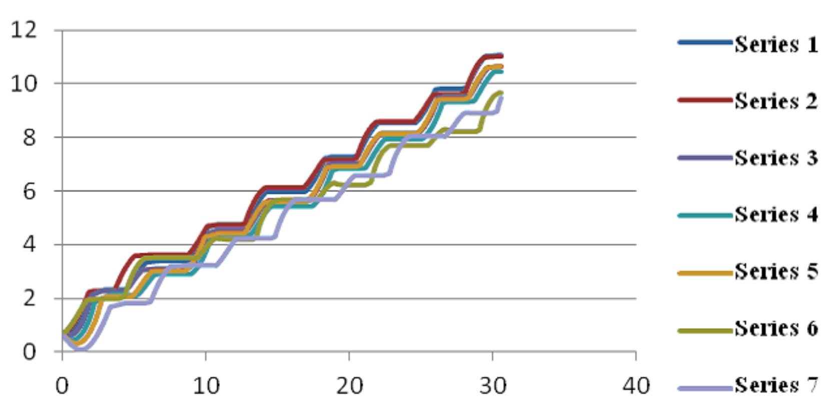


FIG. 2

Further FIG. 3 illustrates the simulation of the electrons' motion. This simulation shows that there is a zone of longitudinal phase stability that is approximately equal to $\pi/8$ or slightly more.

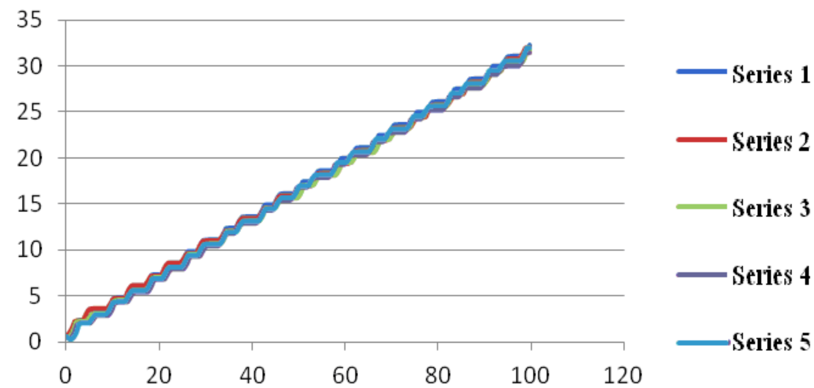
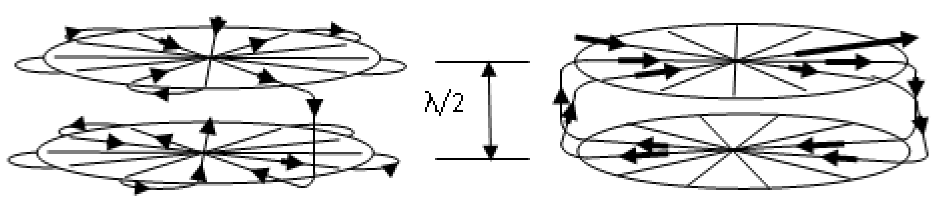


FIG. 3

The number of passages for the Rhodotron is equal to approximately 10-15 passages without increasing the accelerator's frequency, but the miniaturization of such types of accelerators reduces this number. This limit does not allow for an increase in the energy of the electrons and narrows the scope of the accelerator's use. This was the likely reason behind the design of the next generation of accelerators [3] for some applications connected to the increase of electrons' energy at the exit of accelerator. The designing of accelerator, based at the coaxial cavities, with the use of TEM modes of higher order radically changes the situation. They have two or more planes where the radial electrical field in the cavity has maximums [4] and all of the electron beam passages can be placed in these planes. This accelerator is called Multirhodotron. The trajectories of the electron beam in the coaxial cavity can be designed accordingly using variants (a, b) in FIG. 4 and they will be allocated in the first and second planes, where the electric field has maximum amplitude.



(a) (b) FIG. 4

Each of these designs has advantages and disadvantages. Electron bunches will obtain the gain of acceleration with periodicity T in event (a), where T = 1/f and f is the frequency of the accelerator cavity. In the second variant, the beam's bunches will be accelerated with periodicity 1.5 T, but in this case there are some intervals of trajectories under transferring of electrons from one plane to another for the using of additional focusing elements there.

The longitudinal dynamics of the electron beams are identical in both cases. These variants provide the option of miniaturizing the accelerator and working with higher frequencies. For example, an accelerator operating at a frequency of 200 MHz might have an external diameter and cavity height near 1 meter and 3 meters, respectively, with possibility to have four accelerating planes because a cavity height is equal to four halves of the wavelength. This variant allows obtaining approximately 40 passages of the electron beam through the cavity. This could allow increasing an output up to 40-50 MeV without a significant increase of the electromagnetic field in the cavity compared to the operating level of the first generation of Rhodotrons, excluding unjustified growth of losses in the cavity walls.

Similar to the Rhodotron and other resonant accelerators, the Multirhodotron also has significant defects. These include Beam Break Up (BBU) instability that limits the number of passages of the beam through the cavity (or the output energy of the electron beam, accordingly) and limits the level of the electron current too. The Rhodotron has only one plane for the motion of the accelerating electron beam in the cavity and this facilitates reasoning in its scheme. The effect of an instability was found by IBA and it limited the current in TT1000 up to a level of approximately 100 mA, but they do not assert anywhere in their articles that it was obligatory the BBU instability.

If the sources of high-order modes of TEM oscillations act inside of the cavity, then these oscillations will be effectively energized in the cavity. This might be a reason for an appearance of instability in the cavity that depends strongly from the level of current of the accelerated beam.

The most likely reason for this instability is the following dependency. The all even harmonics of TEM (TEM_{2n}, n = 2, 4…) in the middle plane of the Rhodotron's cavity have maximum magnetic fields and electric fields equal to zero. If during one passage the magnetic fields of these modes deflect all electrons of bunches from the middle plane into the area near the middle plane where the electric fields of these oscillations are already not equal to zero, then the electron bunches will be decelerated in the next passage by these electric fields in this area and thus the amplitudes of these modes will increase in the cavity. This dependency can be simply confirmed analytically. This can be also established using experimental measures registering the HOMs oscillations in the cavity by a spectrometer, simultaneously increasing the accelerator's current.

This defect can be easily removed by means of small changes in the cavity that increase the attenuation of HOMs TEM_{2n}, n = 2, 4… . This result can be obtained if two slits are made in the inner and external cylinders of the resonant coaxial cavity in the middle plane and perpendicularly to the cavity axis. The length of the initial whole cavity is equal to $\lambda/2$, but with these slits the whole cavity will consist of two insulated halves of the coaxial cylinders and the length of each of half will

be equal to $\lambda/4$. In this case, all modes of TEM $_{(2n+1)}$, n = 1, 3… that have not currents through the cavity slits, will not be attenuated. However, for all currents for the modes TEM_{2n}, n = 2, 4... in the cavity walls that cross these slits the energizing conditions of these oscillations will not be met.

The analogical method can also be used for the Multirhodotron to allow a larger number of electron beam passages through the cavity, especially if there are two, three, or four planes for the electron beam to move through the cavity. The aforementioned method can also enable an increase of the current of electron beam under acceleration in the Multirhodotron.

Increasing the number of passages through the accelerating cavity may be used not only to increase the energy at the exit of accelerator, but also for obtaining two, three, or four electron beams with different parameters at several exits of a single accelerator for instance for the multilateral irradiation of objects under the radiation treatment.

Using an increased number of passages of a single electron beam through the Multirhodotron allows a significant increase in efficiency while transforming one kind of electric energy to another. Electron accelerators are often used to excite FEL's wiggler, but the efficiency of transforming the energy of an electron beam in the wiggler into the power of the flow of light at the exit of FEL is approximately 1-2%, therefore an FEL with megawatt output is very expensive in exploiting.

A small loss of the electrons' energy in an accelerated beam after passage through the wiggler leads to considerations regarding returning the rest of the beam's energy into the cavity's electromagnetic field as in the JAERI ERL (energy recovery linac), for example [5]. After crossing the wiggler, the electron beam can be returned to the accelerating area, but only in the phase of the electromagnetic field for the deceleration of the electron beam in the accelerator. But for the Multirhodotron the combination of the accelerating part of the beam with the decelerating part of beam is not mandatory in the same place because the beam's acceleration can be provided in one group of cavity gaps and the deceleration of the beam after crossing the wiggler can be provided in another group of gaps in the same cavity. This follows from equation (2), if it is assumed that $R\omega/c + \varphi_0 = \pi$ and $P_{(0)} = P_{(k)}$, then

$$P_{(k+n)} = P_{(k)} + n\, \Delta P_0 \cos (R\omega/c + \varphi_0 + \Delta\varphi) \approx P_{(k)} - n\, \Delta P_0(1 - 0.5\, \Delta\varphi^{**}2) = P_{(k)} - n\, \Delta P_0(1-0.076) \qquad (3)$$

The simulation of this event shows that the initial area of longitudinal phase stability also exists in the region of deceleration (FIG. 5). Reducing the electrons' energy in this beam can continue almost to zero.

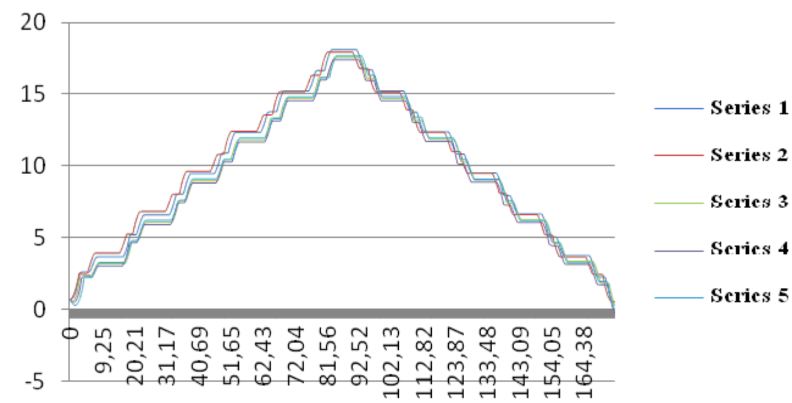
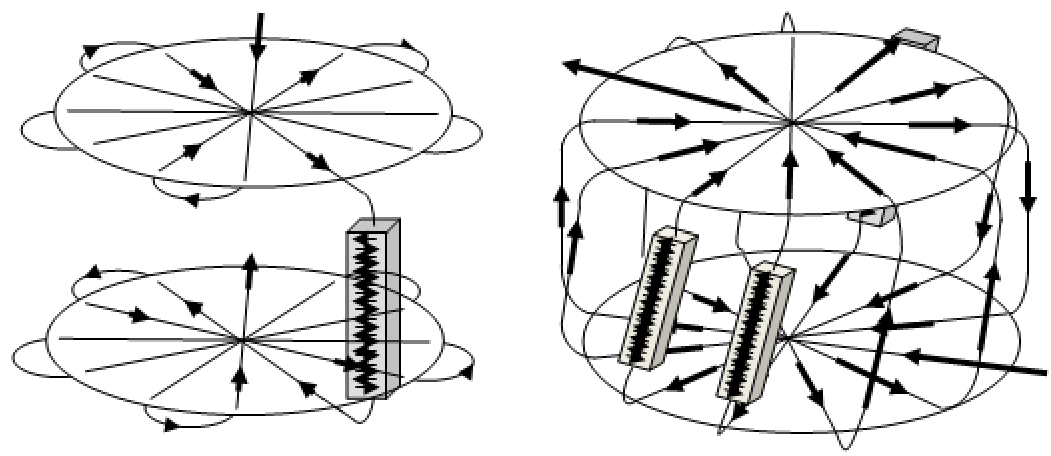


FIG. 5

This variant of FEL was suggested by Etievant in [6]. The FEL on the base of the Rhodotron was investigated by Bassaler and Etievant in [7]. They suggested counting the efficiency of the transformation of microwave energy from the accelerator's generator into the power of flow of an infrared laser on free electrons accordingly with the formula:

$$\eta = \eta_L W_L / (W_C + \eta_L W_L) \quad (4),$$

where W_C is the average power of the losses in the cavity, η_L is the efficiency of the electron radiation in the wiggler, and W_L is the average power of the electron flow.



(a) (b) FIG. 6

Considering variant of FEL on the basis of parameters which are close to parameters of the most powerful Rhodotron (TT 1000), but with double the number of passages as in the Multirhodotron, allow to assume that the losses in the cavity will be W_L = 700 kW and W_C = 500 kW If to take into account in this case that η_L=0.01`the efficiency will be η = 0.023, which remains

insufficient for widespread application. By the way, how it follows out of (4), the significant result of increasing for efficiency (more 0.5) will be obtained if (η_L W_L) will become close with meaning of losses in cavity W_C. There are two possible methods to achieve this.

The first method consists of increasing the energy of the electrons in the accelerating beam of the accelerator exit. This energy can be increased up to 20 MeV for example because in this case, the wavelengths of radiated light will be equal to about 10 microns coinciding with the wavelength of a CO_2 laser, which is the most powerful gas laser in the CW mode and which was designed 50 years ago for exit power up to 50-100 kW. Constructions of all optic lenses and mirrors for these levels of power and wavelengths are well known. Also, suppression of BBU instability in the coaxial cavity may enable an increase of the average meaning of beam's current in the accelerator from 0.1 up to 0.5-1 amperes, but so that in impulse the meaning of current in the accelerator will not exceed the current's limit provided by the focusing forces in the cavity [8] under acceleration 1 MeV per passage, similar to the Rhodotron TT-1000. This method attains an efficiency of $\eta = 0.167$ for 0.5 ampere and $\eta = 0.286$ for 1 ampere accordingly and allows to reach approximately 100-200 kW at the exit of FEL (FIG. 6a).

The second method consists of increasing η_L. In an undulator, the efficiency is equal to 1-2% in practice. This meaning may be slightly increased by means of variation of the gap's magnetic field along the wiggler and its length, for instance, as in a "tapered wiggler." Significant the increase of this parameter can be achieved if the beam passes through two, three, or more wigglers connected in series or in parallel, and the beam's radiation will be at the same wavelength in each wiggler. This effect could be provided if after each passage through the wiggler the energy of the electrons in the beam would differ slightly from the main meaning at the exit. For each passage, the incremental meaning of the electrons' energy is determined by the accelerator's design and cannot be changed arbitrarily, but these levels of energy will differ approximately in 5-10% from the exit meaning in 20 MeV. The radiation losses of the electrons' energy for 20 MeV will be equal to 200 kV, that will be even less than the increase of energy per one passage under acceleration. The Multirhodotron has a number of possible passages more than the Rhodotron therefore this feature provides a simple solution of increase of wiggler's number. If after each passage of the beam through one wiggler, the beam comes back to the accelerator, the parameters of other wiggler can compensate the difference in energy (5-10%), because the wavelength of radiation depends on the wiggler's parameters by means of the following formula:

$$\lambda = (1 + \alpha^2{}_w/2)\, \lambda_0/2\gamma^2 \qquad (5)$$

where $\alpha_w = e_0B_0 \lambda_0/(2\pi m_0c)$ and λ_0 is the period of the undulator.

A variant of this FEL based on the Multirhodotron is described in FIG. 6 (b) for three wigglers. If the FEL is constructed under this scenario with five wigglers, then the efficiency for currents of 0.5 and 1 amperes will be equal to $\eta_{0.5} = 0.5$ and $\eta_1 = 0.67$, respectively. These scenarios might provide practical applications with the level of radiation power in 0.5-1 MW.

In the first case, with a beam current of 0.5 amperes, the accelerator can have an ordinary HF generator on the basis of the Diacrode TH-628, similar to the Rhodotron TT-1000. An increase of the number of wigglers provides greater efficiency, for instance, up to η=0.8-0.9, but then more powerful HF generators are necessary. This problem can be resolved either by the using of 2-3 tetrodes in parallel in the generator as in [9] or by the use of a two-beam accelerator as in [10].

The Multirhodotron with 40 passages through the coaxial cavity enables the achievement of two important practical industrial tasks. One of them is the manufacture of medical isotopes using an electron beam with an output energy about 40 MeV instead of nuclear reactors. The second task is the transforming the energy of electricity into the energy of flow of light in the infrared range with high efficiency at the level of energy approximately in 1 MW.

Another important application of the Multirhodotron with the back return of the electrons energy that remained after the beam's using as the sources of high-current and high-energy electrons' beams is the use of the electron beam in technology of "electron cooling." Almost all ion and proton accelerators and colliders are equipped with devices for "electron cooling" to increase the luminosity of these ion and proton beams. In the 1970s, electron cooling systems used DC accelerators of 2-4 MeV with currents up to 1 ampere. In 2006, new ideas were suggested for electron cooling technology. This technology used a bunched electron beam with energy of approximately 54 MeV and with an average current up to 0.5 ampere that was produced by the superconductivity linac with the using ERL technology. The accelerator had four sections with five cells in each for a frequency of approximately 705 MHz, as described in [11], for the planned cooling of a beam at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Such parameters of the electron accelerator lie in the range that can be covering by the Multirhodotron. More over the recuperation technologies of the beam's energy in the project like JAERI ERL and others, which also are using the superconductivity linacs, are not so simple for implementation. And these projects demand too much squares for the placing of such constructions.

A miniaturized Multirhodotron would better manage this task, if abovementioned features of Multirhodotron could be technically implemented.

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